

## REPORT DOCUMENTATION PAGE

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		5c. PROGRAM ELEMENT NUMBER 611103		
6. AUTHORS Z. Celinski		5d. PROJECT NUMBER		
		5e. TASK NUMBER		
		5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of Colorado - Colorado Springs Regents of the Univ. of CO/Univ of CO at Colorado Springs 1420 Austin Bluffs Parkway Colorado Springs, CO 80918 -		8. PERFORMING ORGANIZATION REPORT NUMBER		
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14. ABSTRACT Our work concentrated on on-wafer delay lines based on liquid crystals. These non-dispersive devices were tested in the range of 1- 110 GHz and exhibit phase change on the order of 300 deg./cm. We have designed also series of other tunable devices based on liquid crystals such as band pass and notch filters and patch antennas operating at 60 and 85 GHz. The nonlinear effects of two wave mixing were studying in magnetic structures. It allowed us to amplify the weak signal by 25 dB as well as to create the comb of frequencies equally spaced. We also developed a				
15. SUBJECT TERMS On Wafer Microwave Devices, Study of Material Properties in the the GHz range				
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				19b. TELEPHONE NUMBER 719-255-3583

## Report Title

### Giga-Hertz Electromagnetic Wave Science and Devices for Advanced Battlefield Communications

#### **ABSTRACT**

Our work concentrated on on-wafer delay lines based on liquid crystals. These non-dispersive devices were tested in the range of 1- 110 GHz and exhibit phase change on the order of 300 deg./cm. We have designed also series of other tunable devices based on liquid crystals such as band pass and notch filters and patch antennas operating at 60 and 85 GHZ. The nonlinear effects of two wave mixing were studying in magnetic structures. It allowed us to amplify the week signal by 25 dB as well as to create the comb of frequencies equally spaced. We also developed a deposition process (Metallo-organic decomposition – MOD) of hexagonal ferrites on metallic templates (Pt). Finally, we demonstrated the feasibility of using hexagonal ferrite thin films to develop planar millimeter wave phase shifters and notch filters.

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#### **List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:**

##### **(a) Papers published in peer-reviewed journals (N/A for none)**

List of papers:

1. R. Lehndorff, D. E. Bürgler, C. M. Schneider, and Z. Celinski, "Injection locking of the gyrotropic vortex motion in a nanopillar", *Appl. Phys. Lett.*, 97, 142503 (3pp) (2010)
2. V.V. Zagorodnii, A. J. Hutchison, S. Hansen, Jue Chen, H.H. Gatzen, and Z. Celinski, "Broad-band FMR characterization of lossy ferromagnetic metallic elements", *J. Appl. Phys.*, 107, 113906 (2010)
3. Yan Nie, I. Harward, K. Balin, A. Beaubien, and Z. Celinski, "Preparation and characterization of barium hexagonal ferrite thin films on a Pt template", *J. Appl. Phys.*, 107, 073903 (2010)
4. Y.V. Khivintsev, Bijoy Kuanr, T.J. Fal, M. Haftel, R.E. Camley, Z.J. Celinski, and D.L. Mills, "Nonlinear ferromagnetic resonance in permalloy films: A nonmonotonic power dependent frequency shift", *Phys. Rev. B*, 81, 054436 (2010)
5. Y. V. Khivintsev, L. Reisman, J. Lovejoy, R. Adam, C. M. Schneider, R. E. Camley, and Z. J. Celinski, "Spin wave resonance excitation in ferromagnetic films using planar waveguide structures", *J. Appl. Phys.* 108, 023907 (2010)
6. Zihui Wang, Young-Yeal Song, Yiyan Sun, Bevvino J., Wu M., Veerakumar V., Fal T.J., Camley R.E., "Millimeter wave phase shifter based on ferromagnetic resonance in a hexagonal barium ferrite thin film", *Appl. Phys. Lett.*, 97, 072509 (3 pp.), 2010
7. K.L.Livesey and R.E. Camley, "Magnetic metal cladding gives better attenuation in small waveguides operating at high microwave frequencies than nonmagnetic metals, *Appl. Phys. Lett.*, 96, 252506 (3pp) 2010
8. V. Veerakumar and R.E. Camley, "Magnetostatic bulk and surface spin-wave focusing in antiferromagnetic thin films", *Phys. Rev. B*, 81, 174432 (8pp) 2010
9. Ryan K. Smith, Marek Grabowski, and R.E. Camley, Period doubling toward chaos in a driven magnetic macrospin *J. Mag. Mag. Mater.*, 322, 2127-2134 (2010)
10. T.J. Fal and R.E. Camley, "Microwave assisted switching in bit petterned media: Accessing multiple states", *Appl. Phys. Lett.*, 97, 122506 (2010)
11. "Self-biased planar millimeter wave notch filters based on magnetostatic wave excitation in barium hexagonal ferrite thin films," Young-Yeal Song, Yiyan Sun, Lei Lu, Joshua Bevvino, and Mingzhong Wu, *Appl. Phys. Lett.* 97, 173502 (2010).
12. "Electric-field control of ferromagnetic resonance in monolithic BaFe<sub>12</sub>O<sub>19</sub>-Ba<sub>0.5</sub>Sr<sub>0.5</sub>TiO<sub>3</sub> heterostructures," Jaydip Das, Young-Yeal Song, and Mingzhong Wu, *J. Appl. Phys.* 108, 043911 (2010).
13. "Millimeter wave phase shifter based on ferromagnetic resonance in a hexagonal barium ferrite thin film," Zihui Wang, Young-Yeal Song, Yiyan Sun, Joshua Bevvino, Mingzhong Wu, V. Veerakumar, Timothy J. Fal, and Robert E. Camley, *Appl. Phys. Lett.* 97, 072509 (2010).
14. "Electric tuning of ferromagnetic resonances in hexagonal-barium-ferrite/barium-strontium-titanate heterostructures," Young-Yeal Song, Jadip Das, Pavol Krivosik, Hyung-Kee Seo, and Mingzhong Wu, *IEEE Magn. Lett.* 1, 2500204 (2010).
15. "Formation of random dark envelope solitons from incoherent waves," Wei Tong, Mingzhong Wu, Lincoln D. Carr, Boris Kalinikos, *Physical Review Letters* 104, 037207 (2010).
16. "Millimeter wave notch filters based on ferromagnetic resonance in hexagonal barium ferrites," Young-Yeal Song, César L. Ordóñez-Romero, and Mingzhong Wu, *Applied Physics Letters* 95, 142506 (2009).

**Number of Papers published in peer-reviewed journals:** 16.00

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##### **(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)**

**Number of Papers published in non peer-reviewed journals:** 0.00

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**(c) Presentations**

**Number of Presentations:** 0.00

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**Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

**Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):** 0

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**Peer-Reviewed Conference Proceeding publications (other than abstracts):**

1. Z.Celinski "On-wafer microwave devices" AMRI Review and Symposium, New Orleans, February 2010 (invited)
2. Z.Celinski "On wafer microwave phase shifters and isolators.", International Conference on Microwave Magnetics", June 2010, Boston (Invited)
3. R. E. Camley, T. J. Fal, Y. Khivintsev, Z. Celinski, "Nonlinear Magnetic Dynamics", Magnetic North Converence, London, Ontario, Canada June 2010
4. R. E. Camley, T. J. Fal, Y. Khivintsev, Z. Celinski "Nonlinear Magnetic Dynamics", Canadian Association of Physics, Toronto, Canada June 2010
5. "Millimeter wave phase shifters and filters based on barium hexagonal ferrite thin films," Mingzhong Wu, Young-Yeal Song, Lei Lu, Zihui Wang, Yiyan Sun, and Joshua Bevivino, Seminar in the Department of Electrical and Computer Engineering, the University of Alabama, October 27, 2010. (Invited talk)
6. "Electric tuning of ferromagnetic resonance in monolithic ferromagnetic-ferroelectric heterostructures," Mingzhong Wu, Young-Yeal Song, Yiyan Sun, and Jaydip Das, the XIX International Materials Research Congress, Cancun, Mexico, August 16, 2010. (Invited talk)
7. "Electric tuning of ferromagnetic resonance in layered ferromagnetic-ferroelectric heterostructures," Mingzhong Wu, Seminar in the College of Physics, Central South University, Changsha, July 16, 2010. (Invited)
8. "Electric tuning of ferromagnetic resonance in layered ferromagnetic-ferroelectric heterostructures," Mingzhong Wu, Seminar in the Department of Electronics Science and Technology, Huazhong University of Science and Technology, Wuhan, July 13, 2010. (Invited)
9. "Electric tuning of ferromagnetic resonance in layered ferromagnetic-ferroelectric heterostructures," Mingzhong Wu, Seminar in the Functional Materials Research Laboratory at Tongji University, Shanghai, July 7, 2010. (Invited talk)
10. "Electric tuning of ferromagnetic resonance in monolithic ferromagnetic-ferroelectric heterostructures," Mingzhong Wu, Colloquium in the Department of Electrical and Computer Engineering, the George Washington University, Washington DC, May 19, 2010. (Invited talk)  
Presentation of Contributed
11. Y. V. Khivintsev; L. Reisman; R. Adam; C. M. Schneider; R. E. Camley and Z. Celinski, "Spin wave resonance excitation in ferromagnetic films using planar waveguide structures", 55th Annual Conference on Magnetism and Magnetic Materials, Atlanta, Nov. 14-18 (Session CD-9)
12. B. K. Kuanr; V. Venugopal; Y. Khivintsev; R. E. Camley; Z. Celinski, "Magnetically tuned High Frequency Phase Shifter using Fe as active element", 55th Annual Conference on Magnetism and Magnetic Materials, Atlanta, Nov. 14-18 (Session CU-12)
13. V. V. Zagorodnii; A. J. Hutchison; S. Hansen; J. Chen; Z. Celinski; H. H. Gatzen, "Broad-band FMR characterization of lossy ferromagnetic metallic elements", 55th Annual Conference on Magnetism and Magnetic Materials, Atlanta, Nov. 14-18 (Session CW-03)
14. V. Venugopal; B. K. Kuanr; L. M. Malkinski; M. Yu; R. E. Camley; Z. Celinski "Tunable local band pass filter using permalloy square antidot arrays", 55th Annual Conference on Magnetism and Magnetic Materials, Atlanta, Nov. 14-18 (Session FH-06)
15. Z.Wang, Y. Song, Y. Sun, J. Bevivino, M.Wu, V. Veerakumar, T.J. Fal and R.E. Camley, "Hexagonal barium ferrite thin film-based millimeter wave phase shifters", 55th Magnetism and Magnetic Materials Conference, Atlanta, Georgia, Nov 2010, (Session HE-03)
16. I. Harward, Y. Nie, K. Balin, A. Beaubien, Z. Celinski, Preparation And Characterization Of BaFe12O19 Thin Films On A Pt, 7th MML Conference, Berkeley, September 2010 (Session Mo-7)
17. Nie, Yan, Harward, I.; Balin, K.; Beaubien, A.; Celinski, Z., Preparation and characterization of barium hexagonal ferrite thin films on a Pt template" 11th Joint MMM-Intermag Conference, Washington DC, January 2010
18. T. Fal and R.E.Camley, "Multiple State Switching for Magnetic Bit Patterned Media through the Use of Microwave Assisted Magnetic Reversal", MMM Conference, Washington D. C. (2010)
19. "Hexagonal barium ferrite thin film-based millimeter wave phase shifters," Zihui Wang, Young-Yeal Song, Yiyan Sun, Joshua Bevivino, Mingzhong Wu, V. Veerakumar, Timothy J. Fal, and Robert E. Camley, the 55th Annual Conference on Magnetism and Magnetic Materials, Atlanta, Georgia, November 14-18, 2010. (Contributed talk)
20. "In-plane c-axis oriented barium ferrite films with both low loss and high remanent magnetization," Young-Yeal Song, Yiyan Sun, and Mingzhong Wu, the 55th Annual Conference on Magnetism and Magnetic Materials, Atlanta, Georgia, November 14-18, 2010. (Contributed talk)
21. "Planar millimeter wave notch filters based on magnetostatic wave resonance in barium hexagonal ferrite thin films," Lei Lu, Young-Yeal Song, Joshua Bevivino, and Mingzhong Wu, the 2010 APS Four Corners Section Fall Meeting, Ogden, Utah, October 15-16, 2010. (Contributed talk)
22. "Hexagonal barium ferrite thin film-based millimeter wave phase shifters," Zihui Wang, Young-Yeal Song, Yiyan Sun, Joshua Bevivino, Mingzhong Wu, V. Veerakumar, Timothy J. Fal, and Robert E. Camley, the 2010 APS Four Corners Section Fall Meeting, Ogden, Utah, October 15-16, 2010. (Contributed talk)
23. "Monolithic electrode-yttrium iron garnet-barium strontium titanate-electrode heterostructures for electrically tunable microwave devices," Young-Yeal Song, Yiyan Sun, and Mingzhong Wu, the 2010 International Conference on Microwave Magnetics, Boston, June 1-4, 2010. (Contributed talk)
24. "Electric field tuning of ferromagnetic resonances at 60 GHz in monolithic barium ferrite – barium strontium titanate heterostructures," Young-Yeal Song, Jaydip Das, Pavol Krivosik, Hyung-Kee Seo, and Mingzhong Wu, the 2010 International Conference on Microwave Magnetics, Boston, June 1-4, 2010. (Contributed talk)
25. "Hexagonal barium ferrite-based millimeter wave notch filters," Young-Yeal Song, Cesar Ordonez Romero, and Mingzhong Wu, the 11th Joint MMM/Intermag Conference, Washington DC, January 18-22, 2010. (Contributed talk)
26. "Electric field-tunable ferromagnetic resonance responses in barium ferrite-barium strontium titanate monolithic structures," Young-Yeal Song, Jaydip Das, Pavol Krivosik, and Mingzhong Wu, the 11th Joint MMM/Intermag Conference, Washington DC, January 18-22, 2010. (Contributed talk)

**(d) Manuscripts**

**Number of Manuscripts:** 0.00

**Patents Submitted****Patents Awarded****Awards****Graduate Students**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Tim Fal	1.00
Ian R Harward	0.50
Jeff Marsh	0.20
Yiyan Sun	0.30
Aaron Hagerstrom	0.30
<b>FTE Equivalent:</b>	<b>2.30</b>
<b>Total Number:</b>	<b>5</b>

**Names of Post Doctorates**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Veerakumar Venugopal	1.00
Pavol Krivosik	0.80
Karen Livesey	0.40
<b>FTE Equivalent:</b>	<b>2.20</b>
<b>Total Number:</b>	<b>3</b>

**Names of Faculty Supported**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Zbigniew Celinski	0.20	No
Robert Camley	0.20	No
Mingzhong Wu	0.20	No
<b>FTE Equivalent:</b>	<b>0.60</b>	
<b>Total Number:</b>	<b>3</b>	

**Names of Under Graduate students supported**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Lindsay Riesman	0.20
<b>FTE Equivalent:</b>	<b>0.20</b>
<b>Total Number:</b>	<b>1</b>

### **Student Metrics**

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ..... 1.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 1.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 1.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 1.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: ..... 1.00

### **Names of Personnel receiving masters degrees**

NAME

**Total Number:**

### **Names of personnel receiving PHDs**

NAME

**Total Number:**

### **Names of other research staff**

NAME

PERCENT SUPPORTED

**FTE Equivalent:**

**Total Number:**

### **Sub Contractors (DD882)**

1 a. Colorado State University - Ft. Collins

1 b. Sponsored Programs

601 South Howes St., 408 University Se

Fort Collins

CO

805232002

**Sub Contractor Numbers (c):** 73082

**Patent Clause Number (d-1):** N/A

**Patent Date (d-2):** 11/11/1111 12:00:00AM

**Work Description (e):** Studies of non linear effects in hexagonal ferrites and YIG.

**Sub Contract Award Date (f-1):** 12/1/2008 12:00:00AM

**Sub Contract Est Completion Date(f-2):** 9/15/2010 12:00:00AM

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1 a. Colorado State University - Ft. Collins

1 b. Office of Sponsored Programs

Colorado State University

Fort Collins

CO

805232002

**Sub Contractor Numbers (c):** 73082

**Patent Clause Number (d-1):** N/A

**Patent Date (d-2):** 11/11/1111 12:00:00AM

**Work Description (e):** Studies of non linear effects in hexagonal ferrites and YIG.

**Sub Contract Award Date (f-1):** 12/1/2008 12:00:00AM

**Sub Contract Est Completion Date(f-2):** 9/15/2010 12:00:00AM

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### **Inventions (DD882)**